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Eric Badouel, Philippe Darondeau

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UNITÉ DE RECHERCHE
INRIA-RENNES

Institut National
de Recherche
en Informatique
et en Automatique

Domaine de Voluceau
Rocquencourt
B.P. 105
78153 Le Chesnay Cedex
France
Tél.: (1) 39 63 55 11

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A NOTE ON GUARDED RECURSION

Eric BADOUEL
Philippe DARONDEAU

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Campus Universitaire de Beaulieu
35042 - RENNES CÉDEX
FRANCE
Téléphone : 99 36 20 00
Télex : UNIRISA 950 473 F
Télécopie : 99 38 38 32

A note on guarded recursion

Eric Badouel - Philippe Darondeau
Irisa, Campus de Beaulieu , 35042 Rennes Cedex

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Abstract : *We introduce a logical notion of well-guardedness for recursive terms on arbitrary signatures defined in Plotkin's framework of structural operational specifications, restricted by de Simone's realizability requirements. We then suggest a simpler form for the logical rule that gives the behaviour of a recursively defined expression in terms of the behaviour of its unfoldings. For well-guarded terms, the simplified rule is logically equivalent to the general rule, but it has not the drawback to ask for premises more complex than consequences.*

Une note sur la récursion gardée

Résumé : *Nous définissons sur des bases logiques la notion d'expression récursive bien gardée. Celle-ci est paramétrée par un ensemble de spécifications opérationnelles respectant le format introduit par Robert de Simone. Nous suggérons alors une forme simplifiée pour la règle qui identifie le comportement d'une expression récursive aux comportements de ses dépliages syntaxiques. Lorsqu'on se restreint aux expressions bien-gardées, la règle simplifiée s'avère logiquement équivalente à la règle générale, mais a l'avantage de ne pas introduire de prémisses structurellement plus complexes que les conclusions.*

ADP (100%) is completely converted to ATP (100%) in the presence of the electron transport chain and oxygen. The electron transport chain is a series of protein complexes that transfer electrons from one molecule to another, creating a proton gradient across the membrane. This gradient is used to drive the synthesis of ATP from ADP and inorganic phosphate (Pi).

A note on guarded recursion

Eric Badouel - Philippe Darondeau

Irisa, Campus de Beaulieu , 35042 Rennes Cedex - France

Abstract

We introduce a logical notion of well-guardedness for recursive terms on arbitrary signatures defined in Plotkin's framework of structural operational specifications, restricted by de Simone's realizability requirements. We then suggest a simpler form for the logical rule that gives the behaviour of a recursively defined expression in terms of the behaviour of its unfoldings. For well-guarded terms, the simplified rule is logically equivalent to the general rule, but it has not the draw-back to ask for premises more complex than consequences.

Let there be given a signature Σ and a denumerable set of variables X , and let $T(\Sigma, X)$ be the set of 'recursive' terms over X defined by the BNF syntax

$$t ::= x \mid f(t_1, \dots, t_n) \mid \text{rec } x.t$$

where $x \in X$, $f \in \Sigma_n$ is an operator of arity n and $\text{rec } x$ binds recursively x to the operand t , entailing the usual notions of free and bound variable. As usual, substitution operations bear upon free variable : $t[u/x]$ stands for the term t in which each free occurrence of x has been replaced by u (after possible renaming of bound variables in t). When closed terms are considered as programs, their behaviour is specified by the elementary transitions $t \xrightarrow{\lambda} u$ a program can perform (the transition $t \xrightarrow{\lambda} u$ reads as "t may perform the action λ and then behave as u"). Following the method known as Structural Operational Semantics (SOS in short) advocated by Plotkin [Plo81], those transitions are defined as the formulae provable in a deductive system. As a concrete example, let us consider the restriction of CCS [Mil80] defined as follows. There is a set of actions $A = \Lambda \cup \{\tau\}$ where τ is the so-called *invisible action* and Λ is equipped with an involutive mapping of synchronization $(\bar{}) : \Lambda \rightarrow \Lambda$; the complementary actions λ and $\bar{\lambda}$ are those taking place in a communication (delivering and reception of a message). The signature $\Sigma = \Sigma_0 \cup \Sigma_1 \cup \Sigma_2$ offers a constant for inaction : $\Sigma_0 = \{\text{nil}\}$, together with operators for prefixing by an action in Λ : $\Sigma_1 = \{\lambda.- ; \lambda \in \Lambda\}$, and with two binary operators

for non deterministic choice and parallel composition : $\Sigma_2 = \{+; \parallel\}$. The behaviour of programs is specified by the rules :

$$\begin{array}{lcl}
\text{nil} & : & \\
\lambda.- & : & \lambda.t \xrightarrow{\lambda} t \\
+ & : & \frac{t \xrightarrow{\lambda} t'}{t + u \xrightarrow{\lambda} t'} \quad \frac{u \xrightarrow{\lambda} u'}{t + u \xrightarrow{\lambda} u'} \\
\parallel & : & \frac{t \xrightarrow{\lambda} t'}{t \parallel u \xrightarrow{\lambda} t' \parallel u} \quad \frac{u \xrightarrow{\lambda} u'}{t \parallel u \xrightarrow{\lambda} t \parallel u'} \quad \frac{t \xrightarrow{\lambda} t', u \xrightarrow{\bar{\lambda}} u'}{t \parallel u \xrightarrow{\tau} t' \parallel u'}
\end{array}$$

Those rules are used in conjunction with a specific rule for recursion, stating that a term behaves as any of its syntactical unfoldings. The CCS-rule is the following :

$$\frac{u[\mathbf{rec} \ x.u/x] \xrightarrow{\lambda} v}{\mathbf{rec} \ x.u \xrightarrow{\lambda} v} \quad \mathbf{rec}_1$$

Generalizing on the above example, we will consider the rule \mathbf{rec}_1 in conjunction with arbitrary rules in de Simone's format [dS84]. A set of SOS rules is in *de Simone's format* when there is, for each operator $f \in \Sigma_n$, a finite set of schemes of rules which conform to the following pattern :

$$\frac{u_{i_1} \xrightarrow{\lambda_1} v_{i_1}, \dots, u_{i_k} \xrightarrow{\lambda_k} v_{i_k}}{f(u_1, \dots, u_n) \xrightarrow{\lambda_0} C[v_1, \dots, v_n]} \quad R(\lambda_0, \lambda_1, \dots, \lambda_k)$$

where :

- $u_1, \dots, u_n, v_{i_1}, \dots, v_{i_k}$ are different meta-variables taken in a new alphabet, and u_{i_1}, \dots, u_{i_k} are all distinct ($\{u_{i_1}, \dots, u_{i_k}\} \subseteq \{u_1, \dots, u_n\}$),
- for $j \notin \{i_1, \dots, i_k\}$, $v_j = u_j$,
- $t = C[v_1, \dots, v_n]$ is a term over $\{v_1, \dots, v_n\}$ in which each meta-variable v_j occurs at most once and that include no recursive operator $\mathbf{rec} \ x$ nor variable $x \in X$, and
- the side condition $R(\lambda, \lambda_1, \dots, \lambda_k)$ is a recursive predicate of $n + 1$ variables, where λ_i ranges over a recursive set of actions Λ .

The satisfaction of those conditions ensures the 'reliability' of the specified operators in Meije [Bou85]. De Simone's realizability requirements allow neither duplication of arguments u_1, \dots, u_n by the specified operator f , nor lookahead in their structure. Hence the specified operators f may just synchronize the transitions of their operands. Relying on that structural property, we will prove that the rule \mathbf{rec}_1 may be replaced by a simpler rule, in the absence of unguarded recursion, namely

by the following :

$$\frac{u \xrightarrow{\lambda} v}{\text{rec } x.u \xrightarrow{\lambda} v[\text{rec } x.u/x]} \quad \text{rec}_2$$

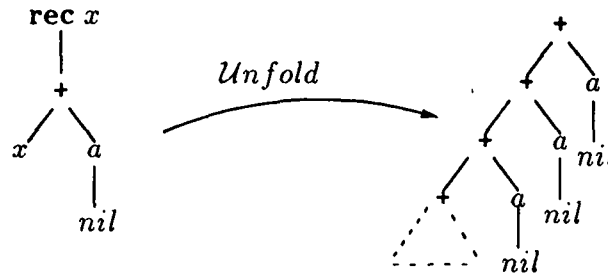
In CCS the prefixing operators $\lambda.-$ are *guards* because their parameter is preserved until the guard-action λ has been performed. This is reflected by the fact that the only rules concerning guard operators are axioms (i.e. rules with empty premises : $k = 0$). The following definition is a straightforward generalization of the notion of guards to arbitrary signatures.

Definition 1 (guard operators and well-guardedness)

Let there be given a signature Σ and a fixed set of SOS rules for the operators in Σ , then

1. $f \in \Sigma_n$ is a **guard-operator** if the only rules concerning that operator are axioms.
2. A variable $x \in X$ is **guarded** in a term $t \in T(\Sigma, X)$ if every free occurrence of x in t is under the scope of at least one guard.
3. A recursion $\text{rec } x.t$ is **well-guarded** if x is guarded in t .
4. And, a term u is **well-guarded** if every subterm of u which is a recursion is well-guarded.

It may be shown that an expression is guarded if, and only if, there is at least one guard (and thus an infinity of guards) on every infinite path of the rational tree produced by unfolding ad infinitum the recursive definition of that term. For instance, the expression $\text{rec } x. (x + a.nil)$ is not well-guarded, and this is reflected by the presence in the corresponding rational tree of an infinite path all nodes of which are labelled with the operator $+$, which is not a guard. Using the general form (rec_1)



of the recursion rule, an immediate transition from an unguarded expression (e.g. $\text{rec } x. (x + a.nil)$) may be induced from operators (e.g. the prefixing $a.-$) occurring at an arbitrary depth in the corresponding rational tree. This cannot happen for

well-guarded expressions, since transitions from $f(t_1, \dots, t_n)$ never modify subterms under the scope of guards in the t_i , but by possibly suppressing them. That is the gist of the following lemma which states that if t is under the scope of a guard in $T = u[t/x]$ then any transition from T leaves t unchanged (rewriting and substitution commute) :

Lemma 2 (commutation lemma) *Let there be given a signature Σ and a fixed set of SOS rules for operators in Σ , obeying de Simone's requirements and used in conjunction with the general form rec_1 of the recursion rule. If $u[t/x] \xrightarrow{\lambda} w$ for some variable x guarded in u then $u \xrightarrow{\lambda} v$ for some expression v such that $w = v[t/x]$.*

Proof :

The proof proceeds by induction on the structure of the deduction for the transition $u[t/x] \xrightarrow{\lambda} w$:

- $u = f(u_1, \dots, u_n)$.
Then $u[t/x] = f(u'_1, \dots, u'_n)$ where $u'_i = u_i[t/x]$.
 - The deduction may be the mere application of an axiom :

$$u[t/x] = f(u'_1, \dots, u'_n) \xrightarrow{\lambda} C[u'_1, \dots, u'_n] = w$$

By the same axiom we get $u \xrightarrow{\lambda} C[u_1, \dots, u_n] = v$, and thus $w = v[t/x]$.

- The deduction may be governed by the application of some rule

$$\frac{u'_{i_1} \xrightarrow{\lambda_1} w_{i_1}, \dots, u'_{i_k} \xrightarrow{\lambda_k} w_{i_k}}{u[t/x] = f(u'_1, \dots, u'_n) \xrightarrow{\lambda_0} w = C[w_1, \dots, w_n]} \quad \text{R}(\lambda_0, \lambda_1, \dots, \lambda_k),$$

where $k \neq 0$ (thus f is not a guard), and $w_j = u'_j$ for $j \notin \{i_1, \dots, i_k\}$. As x is guarded in $f(u_1, \dots, u_n)$ and f is not a guard, x is guarded in u_{i_m} . Hence, by induction hypothesis $u_{i_m} \xrightarrow{\lambda_m} v_{i_m}$ for some v_{i_m} such that $w_{i_m} = v_{i_m}[t/x]$. We apply the same rule to deduce the transition

$$u = f(u_1, \dots, u_n) \xrightarrow{\lambda} C[v_1, \dots, v_n] = v \quad \text{where} \quad v_j = u_j \quad \text{for} \quad j \notin \{i_1, \dots, i_k\}.$$

$$\text{And then} \quad v[t/x] = C[v_1[t/x], \dots, v_n[t/x]] = C[w_1, \dots, w_n] = w$$

$$\text{because} \quad \begin{cases} w_{i_m} = v_{i_m}[t/x] & \text{for } m \in \{1, \dots, k\} \\ w_j = u'_j = u_j[t/x] = v_j[t/x] & \text{for } j \notin \{i_1, \dots, i_k\} \end{cases}$$

- $u = \text{rec } y.u'$.
 - $x = y$
Then $u[t/x] = u$ and we get the result with $v = w$ (there is no free occurrence of x in w).

– $x \neq y$

Then $u[t/x] = \text{rec } y.u'[t/x]$ and the transition $u[t/x] \xrightarrow{\lambda} w$ has been inferred from the premise $(u'[t/x])[\text{rec } y.u'[t/x]/y] \xrightarrow{\lambda} w$. We can assume without loss of generality that y does not occur free in t (otherwise, we rename the bound variable y in u in order to avoid the capture of the corresponding free variable of t in the substitution $u[t/x]$). Thus the cause of $u[t/x] \xrightarrow{\lambda} w$ is the transition $(u'[\text{rec } y.u'/y])[t/x] \xrightarrow{\lambda} w$ and the induction on the structure of the deduction applies, yielding v such that $w = v[t/x]$ and $u'[\text{rec } y.u'/y] \xrightarrow{\lambda} v$, wherefrom $u = \text{rec } y.u' \xrightarrow{\lambda} v$ may be infer by the recursion rule rec_1 .

□

We are ready to prove that the alternative rules rec_1 and rec_2 are equivalent in the absence of unguarded recursion. Given a fixed set of SOS rules obeying de Simone's requirements, let SOS_1 and SOS_2 be the respective sets of transitions provable from that system from rec_1 resp. rec_2 .

Proposition 3 *If u is a well-guarded term then $u \xrightarrow{\lambda} v \in \text{SOS}_1$ if, and only if $u \xrightarrow{\lambda} v \in \text{SOS}_2$ and v is then a well-guarded term.*

Proof :

- *We show that $(u \xrightarrow{\lambda} v \in \text{SOS}_1)$ entails $(u \xrightarrow{\lambda} v \in \text{SOS}_2)$*
We proceed by induction on the structure of the recursive term u . The only non-trivial case is when $u = \text{rec } x.u'$ and the transition in SOS_1 has been inferred from the premise $u'[\text{rec } x.u'/x] \xrightarrow{\lambda} v$. The commutation lemma shows the existence of a term v' such that $v = v'[\text{rec } x.u'/x]$ and $u' \xrightarrow{\lambda} v' \in \text{SOS}_1$. Then $u' \xrightarrow{\lambda} v' \in \text{SOS}_2$ by induction hypothesis, wherefrom $u = \text{rec } x.u' \xrightarrow{\lambda} v'[\text{rec } x.u'/x] = v$ may be inferred by the simplified rule for recursion (rec_2).
- *We show that $(u \xrightarrow{\lambda} v \in \text{SOS}_2)$ entails $(u \xrightarrow{\lambda} v \in \text{SOS}_1)$*
We proceed by induction on the structure of the derivation in SOS_2 . The only non-trivial case is when $u = \text{rec } x.u'$, thus $v = v'[\text{rec } x.u'/x]$ for some v' such that $u' \xrightarrow{\lambda} v' \in \text{SOS}_2$. In that case, $u' \xrightarrow{\lambda} v' \in \text{SOS}_1$ by induction hypothesis, and therefore also $u'[\text{rec } x.u'/x] \xrightarrow{\lambda} v'[\text{rec } x.u'/x] \in \text{SOS}_1$, wherefrom $u = \text{rec } x.u' \xrightarrow{\lambda} v'[\text{rec } x.u'/x] = v$ may be inferred by the general rule for recursion (rec_1).

By induction on the deduction we readily verify that if u is a guarded expression, so is v whenever $u \xrightarrow{\lambda} v$ may be infer in either SOS_1 or SOS_2 .

□

A property shared by the rule **rec**₂ and by any rule in de Simone's format is that the terms appearing in the premises are always simpler than the terms appearing in the consequence. That property which doesn't hold for the rule **rec**₁ allows us to reason upon the deductions by the usual induction on the terms. If we suppose that for each term t , the set of actions labelling transitions from t is a finite subset of Λ , defined effectively from t , then the resulting transition system is finitely branching and furthermore recursive : for any term t , the set $\{ \langle \lambda, t' \rangle ; t \xrightarrow{\lambda} t' \}$ is finite, and the set $\{ \langle t, \lambda, t' \rangle ; t \xrightarrow{\lambda} t' \}$ is recursive (as a subset of ω^3 modulo an encoding of Λ and of the set of well-guarded terms -which is readily seen to be recursive-). In fact, for a fixed consequence, there is only a finite number of possible applications of rules deriving that conclusion, and for each application, the left members of the premises are strict subterms of the left member of the consequence. In contrast, when used in conjunction with **rec**₁, de Simone's rules allow us to realize, up to strong bisimulation, any recursively enumerable system of transitions $T \subset Q \times \Lambda \times Q$ (where Λ and Q are identified with recursive sets of numbers), see [dS84] and [Bou85]). Any recursively enumerable transition system may in fact be realized in Meije which is defined operationally by rules in de Simone's format in conjunction with **rec**₁ (although the exact syntax for recursive terms is different from the one presented here).

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